The First *Fermi*-LAT Catalog of Sources Above 10 GeV*

D. Paneque
Max Planck Institute for Physics, Munich, 80805, Germany
J. Ballet
Laboratoire AIM, CEA-IRFU/CNRS/Université Paris Diderot, Service d'Astrophysique, CEA Saclay, 91191 Gifsur Yvette, France
T. Burnett
Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
S. Digel
SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA
P. Fortin
Fred Lawrence Whipple Observatory, Harvard-Smithsonian Center for Astrophysics, Amado, AZ 85645, USA
J. Knoedlseder
CNRS, IRAP, F-31028 Toulouse Cedex 4, France

on behalf of the *Fermi*-LAT collaboration

We present a catalog of γ-ray sources at energies above 10 GeV based on data from the Large Area Telescope (LAT) accumulated during the first 3 years of the *Fermi Gamma-ray Space Telescope* mission. This catalog complements the Second *Fermi*-LAT Catalog, which was based on 2 years of data extending down to 100 MeV and so included many sources with softer spectra below 10 GeV. The First *Fermi*-LAT Catalog of >10 GeV sources (1FHL) has 514 sources, and includes their locations, spectra, a measure of their variability, and associations with cataloged sources at other wavelengths. We found that 449 (87%) could be associated with known sources, of which 393 (76% of the 1FHL sources) are active galactic nuclei. We also highlight the subset of the 1FHL sources that are the best candidates for detection at energies above 50 GeV with ground-based γ-ray observatories.

1. Introduction

Many more γ-ray sources are known in the GeV range than above 100 GeV. The "*Fermi* Large Area Telescope Second Source Catalog" [hereafter 2FGL, Nolan et al. 2012], reports 1873 sources detected at energies above 100 MeV in the first 2 years of *Fermi* science operations. On the other hand, as reported in the TeVCat catalog[1] version 3.400, only 105 sources have been detected with ground-based γ-ray instruments above 100 GeV (VHE)[2], which is substantially fewer than the number of objects reported in 2FGL.

In this manuscript we briefly summarize the ongoing effort within the *Fermi*-LAT collaboration to produce the "The First *Fermi*-LAT Catalog of Sources Above 10 GeV", designated 1FHL. The lower limit of 10 GeV is a good compromise between photon statistics and proximity to the energy range of the ground-based γ-ray instruments. We report on the location, spectral and variability properties of the 514 sources significantly detected above 10 GeV. Many of these sources are already included in the 2FGL catalog, although in that catalog their characterization is dominated by the much larger numbers of γ-rays in the energy range 0.1–10 GeV. Consequently, the characteristics of the sources at the highest *Fermi*-LAT energies might be overlooked because of the lower statistical weight of the most energetic (but less abundant) γ-rays. With its focus on the high-energy data, the 1FHL catalog complements the 2FGL catalog, and is meant to be a sort of "bridge catalog" between the 2FGL and TeVCat.

2. *Fermi*-LAT Sources Above 10 GeV

The *Fermi*-LAT is a γ-ray telescope operating from 20 MeV to > 300 GeV. The instrument is a 4×4 array of identical towers, each one consisting of a tracker (where the photons are pair converted) and a segmented calorimeter (where the energies of the positron-electron pairs are measured). The tracker is covered by an anti-coincidence detector to reject the charged-particle background. Further details on *Fermi*-LAT and its performance can be found in Atwood et al. [2009] and Ackermann et al. [2012].

In this work we utilize *Pass7 Clean* events with energies in the range 10–500 GeV, detected from the beginning of science operations (2008 August 4, MET 239557447) to 2011 August 1 (MET 333849586), cov-

*The material reported in this proceedings is based on the full catalog paper which is currently in preparation within the *Fermi*-LAT collaboration.
[1] http://tevcat.uchicago.edu/
[2] Including recently announced (but not yet published) VHE detections the number is 143.

ering very nearly 3 years[3].

As for the 2FGL analysis, source detection and characterization began with the assembly of a list of 'seeds', candidate sources that were selected for input to the likelihood analysis chain. The seeds were used as input to standard maximum likelihood analysis to jointly optimize the spectral parameters of the candidate sources and to judge their overall significances (§ 2.1). This analysis was implemented in a similar way to the 2FGL analysis. In the final step of the analysis we also searched for candidate counterparts of these 1FHL sources with sources in previous LAT catalogs and sources in known γ-ray emitting classes at other wavelengths (§ 2.2) using the same methods as for the 2FGL source associations. We put special focus on the characterization of the sources associated with active galactic nuclei (AGNs), which constitute the majority of the catalog (§ 2.3), as well as on the identification of candidate sources for VHE detection with current ground-based γ-ray instrumentation (§ 2.4).

2.1. Spectral Analysis

The procedure we followed was similar to what was done for 2FGL. Starting from the list of seeds we divided the sky into a number of Regions of Interest (RoI) covering all source seeds; 561 RoIs were used for 1FHL. Each RoI extends 2°beyond the sources it contains in order to cover the entire PSF as well as allow the background diffuse emission to be well fit. Because the spatial resolution is good above 10 GeV, there is little cross-talk between sources or between RoIs, so global convergence was relatively easy to achieve.

Over the relatively narrow range 10 to 500 GeV, no source was found to have significant spectral curvature, so each spectrum was described by a power-law model. Each RoI is too small to allow characterizing by itself both the Galactic and isotropic diffuse components, so the isotropic level was fixed to the best fit over the entire sky and we left free the Galactic normalization only.

We used the Test Statistic $TS = 2\Delta \log \mathcal{L}$ (comparing the likelihood with and without the source) to quantify the significance of sources. As for the 2FGL analysis, the detection threshold was set to $TS > 25$, corresponding to a significance just over 4σ for 4 degrees of freedom (two for the localization, and two for the spectrum). Sources below that threshold were discarded from the model, except for the a priori known (at >100 MeV) extended sources, which we retained to model the background even when they were not

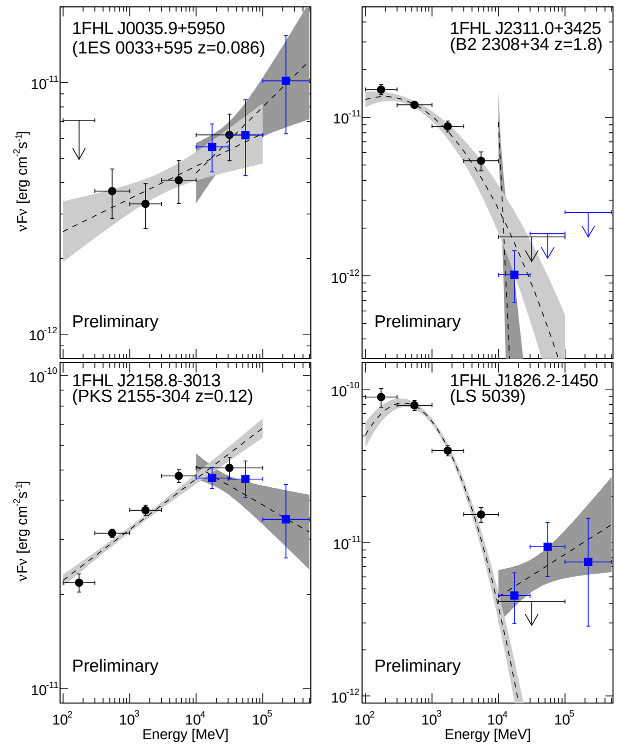

Figure 1: Spectra of four representative 1FHL sources with different spectral shapes above 10 GeV: the 1FHL sources associated with the blazars 1ES 0033+595 (z=0.086), PKS 2155-304 (z=0.117), B2 2308+34 (z=1.8), and with the high-mass binary system LS 5039. The black points and light-grey bands depict the results reported in the 2FGL catalog, while the blue data points and the dark-grey bands depict the spectral results reported in this work. See text for further details.

clearly detected above 10 GeV. No constraint was enforced on the minimum number of γ rays for detected sources, because above 10 GeV and outside the Galactic plane the detection is not background limited. In practice the faintest sources were detected with only 4 γ rays. We used binned likelihood functions as in 2FGL, handling *Front* and *Back* events separately, with 0.05°and 0.1°spatial binning respectively, and 10 energy bins per decade. At the end of the process 514 sources (including 18 extended sources) remained at $TS > 25$ among the 1705 input seeds.

Figure 1 compares the spectral measurements reported in the 2FGL paper (in the 100 MeV to 100 GeV energy range) with the results reported here in the 10–500 GeV energy range, for four representative sources. The blazar 1ES 0033+595 (z=0.086) has a 1FHL spectrum that is a continuation of the 2FGL spectrum, while the classical TeV blazar PKS 2155−304 (z=0.117), which is a few times brighter than the former, shows a clear turnover (from hard to soft spec-

[3]Mission Elapsed Time (MET) starts at 00:00 UTC on 2001 January 1 and does not include leap seconds.

trum) at about 10 GeV. Given that PKS 2155−304 is a relatively nearby source, this turnover must be due to an internal break in the emission mechanism of this source. On the other hand, the spectrum of the distant blazar B2 2308+34 (z=1.8) shows a clear cutoff (strong turnover) around 10 GeV which, given the high redshift of this source, must be dominated by the absorption of γ-rays in the extragalactic background light density (EBL). The fourth panel of Figure 1 shows the 1FHL spectrum of the high-mass binary system LS 5039, which has a completely different shape with respect to the 2FGL spectrum, indicating the presence of a new spectral component. It is worth stressing that, when fitting the sources' spectral shapes over this large dynamic range in energy spanning from 100 MeV to 100 GeV (as performed in the 2FGL), the highest energies have a much lower statistical weight than the lower energies because of the ($\sim$2 orders of magnitude) lower photon count[4], and hence the best-fit spectral shape is determined largely by the lower-energy γ rays. Consequently, the spectral measurements at the highest energies (>10 GeV) can disagree with the 2FGL spectral fits for those sources that have turnovers, cutoffs, and/or new components arising at the highest energies (>10 GeV), as illustrated in Figure 1. These deviations from the simple spectral extrapolation from lower energies indicate the dominance of other physical processes occurring at the source, or in the environment crossed by the γ rays, and hence they are relevant for the proper understanding of these sources. This is naturally one of the important motivations for producing the 1FHL catalog.

2.2. Associations

The 1FHL sources were associated with (known) sources at other wavelengths using similar procedures as for the 2FGL and the "The Second Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope" [hereafter 2LAC, Ackermann et al. 2011].

Of the 514 sources in the 1FHL catalog, we found that 460 were already in the 2FGL catalog, while 54 sources were not. Most of these 1FHL-but-non-2FGL sources are located outside the Galactic plane: 9 blazars, 8 blazar candidates, and a large fraction of the 36 unassociated sources. The star-forming region called the Cygnus cocoon (in the Galactic plane) is also part of this 54-source subset.

Table I Summary of the 1FHL Source Classes

Class Description	Number of Sources	Fraction of Total[a] [%]	Fraction of Associated[b] [%]
Blazar BL Lac	259	50.4	57.7
Blazar FSRQ	71	13.8	15.8
Unknown type AGN	55	10.7	12.2
Pulsar	27	5.2	6.0
Supernova remnant	11	2.1	2.4
Pulsar wind nebula	6	1.2	1.3
Other Galactic	11	2.1	2.4
Other extragalactic	9	1.8	2.0
Unassociated source	65	12.7	—

[a]Fraction relative to the 514 objects in the 1FHL catalog
[b]Fraction relative to the 449 objects with associated sources

The sources that could be associated with sources of known nature (reported in non-γ-ray catalogs) amount to 449. A brief summary of the statistics for the various source classes in the 1FHL catalog is reported in Table I. A remarkable characteristic of this catalog is that the blazars and blazar candidates[5] amount to $\sim$75% of the entire catalog ($\sim$86% of the associated sources), indicating that this source class largely dominates the highest-energy LAT sky. The second largest source class is pulsars, with 5.2% of the catalog total. supernova remnants (SNRs) and pulsar wind nebulae (PWNe) together are only 4.5% of the catalog. Among the sources classified as *other extragalactic*, there are radio galaxies, non-blazar active galaxies, and the nearby galaxy Large Magellanic Cloud (LMC), which, given its proximity, has an extension of 2°; and the sources classified as *other Galactic* are binary systems, globular clusters, and star forming regions, in addition to 6 sources that could be SNRs or PWNe.

From the 65 unassociated 1FHL sources, 5 are associated with extended (Galactic) unidentified H.E.S.S. sources, 25 are associated with unidentified 2FGL sources (including 1 associated with one of the 5 previously-mentioned Galactic H.E.S.S. unidentified sources), 5 are associated with unidentified 1FGL sources, and 2 are associated with unidentified sources from the 3rd EGRET catalog [Hartman et al. 1999]. The remaining 28 sources could not be associated with any γ-ray source reported previously. We note that the fraction of unassociated 1FHL sources is only $\sim$13% (65 out of 514), while the fraction of 2FGL sources in the 1FHL catalog that could not be associ-

[4] For a spectrum parametrized with a power-law function of energy with index α, the ratio between the number of photons above 100 MeV and the number of photons above 10 GeV is given by $(10/0.1)^{\alpha-1}$. For a typical spectrum with $\alpha = 2$, the number of detected photons above 10 GeV would be a factor $\sim$30 less than the number above 100 MeV on consideration of the relative acceptance of the LAT at these two energies.

[5]The fraction of non-beamed AGNs is expected to be only few percent, and hence most of the AGNs of unknown type are expected to be blazars of either FSRQ or BL Lac type.

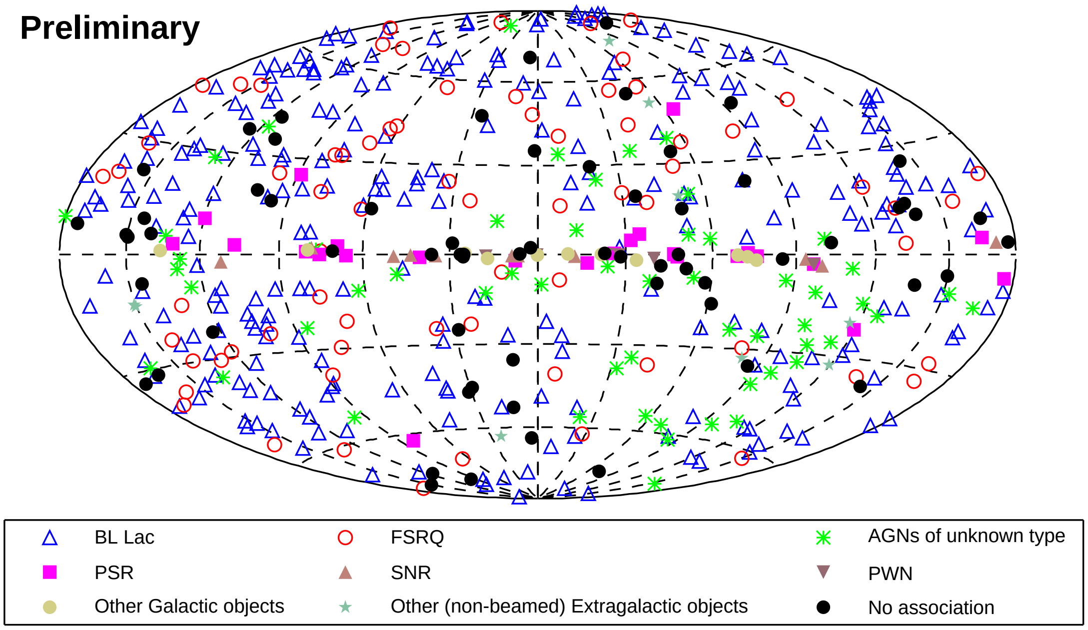

Figure 2: Sky map showing the sources by the source classes reported in Table I

ated is only 6% (25 out of 460). The fraction of unassociated sources reported in the 2FGL catalog was ∼31% (575 out of 1873).

The locations on the sky of the sources in the above-mentioned classes are depicted in Figure 2. To a good approximation, the Galactic sources are located essentially in the Galactic plane (apart from some pulsars), while the blazars are distributed roughly uniformly outside the Galactic plane.

Table II Summary of SED Classifications and Available Redshifts for 1FHL Sources With AGN Associations

SED Classification	Number of Sources	Number of sources with redshift
HSP	162	76
ISP	61	28
LSP	99	75
Not Classified	71	29
Total	**393**	**208**

2.3. Characteristics of the 1FHL AGNs

Table II summarizes the numbers of 1FHL AGN associations belonging to the various SED classifications defined in [Abdo et al. 2010], with and without redshift determinations. Among all blazars, the dominant SED class is *high-synchrotron-peaked* (HSP), which makes up for ∼41% of all the 1FHL AGNs. This is not a surprising result because HSPs typically have a *hard* spectrum (power-law index $\lesssim$2) and hence they are expected to be the AGN source class with the highest-energy photons. Table II also shows that the amount of AGNs with redshift in the 1FHL catalog is 208 (∼53%), from which the fraction of sources with redshift is 47%, 46% and 41% for HSP, *intermediate-synchrotron-peaked* (ISP) and sources without SED classification, and 76% for the class *low-synchrotron-peaked* (LSP). The larger fraction of LSPs with available redshifts is because 58 of the 99 LSPs are actually FSRQs which, *by definition*, have their redshift measured.

Figure 3 shows the distribution of the measured power-law indices of the 1FHL blazars in the energy ranges 100 MeV to 100 GeV (extracted from the 2FGL catalog table) and 10–500 GeV. The figure does not show the nine 1FHL extragalactic sources that are associated with non-blazar AGNs. Note that the number of entries in the distributions in the left-hand panel are less than in the right-hand panel. This is because the 1FHL catalog contains 17 AGN associations (9 BL Lacs and 8 blazar candidates) that do not exist in the 2FGL catalog (§ 2.2). The figure shows a clear softening in the spectra of each source class when the minimum energy is increased from 100 MeV to 10 GeV. This is due to both intrinsic softening of the spectra of many sources[6] and the γ-ray atten-

[6] The intrinsic softening can occur because of internal γ-γ

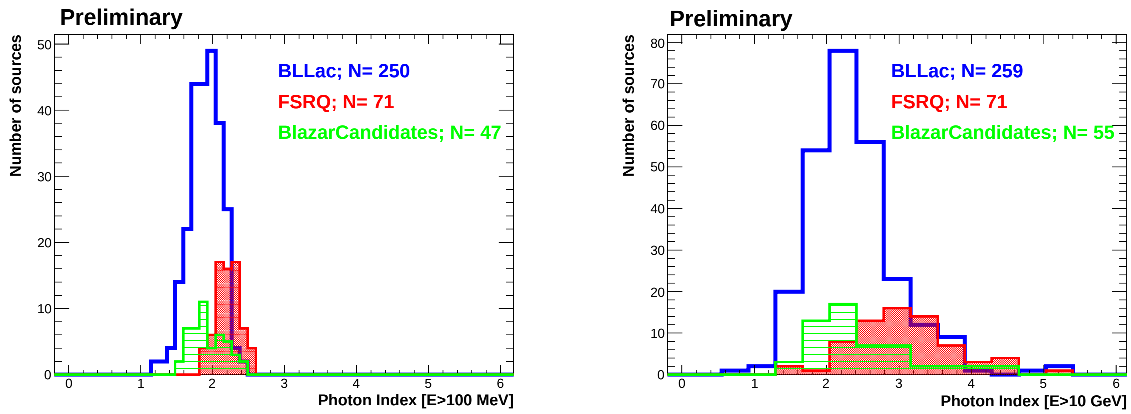

Figure 3: Distribution of measured index for selected groups of 1FHL AGN sources above 100 MeV (*left*, extracted from the 2FGL catalog) and above 10 GeV (*right*, *this work*). The three histograms show the distributions for three different groups of AGN associations: BL Lacs (blue and not-filled histogram), FSRQs (red and dotted-filled histogram), and blazar candidates (green and horizontal-line filled histogram). See text for further details.

uation in the Extragalactic Background optical/UV Light (EBL) for distant ($z > 0.5$) sources. We also note that in both panels the photon indices of the FSRQs cluster at the highest (softest) index values, while BL Lacs have the lowest (hardest) values. So even when the spectra are characterized using photons above 10 GeV, we find that about 30% of the BL Lacs (77 out of 259) have indices harder than 2. The index distribution of the blazar candidates (AGNs of unknown type) is similar to that of BL Lacs, which suggests that a large fraction of these blazar candidates are actually BL Lacs.

Figure 4 shows a scatter plot of the photon index ($E > 100$MeV and $E > 10$ GeV) versus redshift for the various blazar subclasses: FSRQs, HSP-BL Lacs, ISP-BL Lacs, LSP-BL Lacs and BL Lacs without SED classification. There is no redshift evolution in the spectral shape characterized with photon energies above 100 MeV, which is in agreement with the results reported in Figure 19 of the 2LAC paper[7]. However, the photon index computed with energies above 10 GeV depends on the redshift: the sources get softer with increasing redshift. This trend is essentially invisible in the BL Lac sample, which cluster at relatively low redshifts (mostly below 0.5); but it is noticeable in the sample of FSRQs, which extends up to redshift 2.5. A possible explanation for this redshift evolution in the spectral shape measured with photon energies above 10 GeV (but not for the spectral shape computed with photon-energies above 100 MeV) is the attenuation of the γ-rays in the optical/UV density of photons from the EBL, which is energy dependent and only affects photons above a few tens of GeV. In addition, one cannot exclude a potential cosmological evolution of the FSRQ sample that introduces an intrinsic softening of the spectra. However, in order to be consistent with the experimental observation reported in the left/right panels of Figure 4, such a cosmological evolution of FSRQs should affect only the emission above 10 GeV.

Because of the low photon count (~10 photons per source) above 10 GeV, quantifying the variability of the 1FHL sources is very challenging. We used the Bayesian Block algorithm from [Scargle 1998], which is unbinned in time, partitioning the time series data into piecewise constant segments (blocks), characterized by a rate (or flux) and duration. Using the simulation results presented in [Scargle et al. 2013], an acceptable fraction of false positives for detecting variability can be easily specified. For the determination of the variability, we considered a false positive threshold of 1%.

Of the 514 1FHL sources, 43 are significantly variable. The variable sources are each associated with an AGN. Among them, we find 22 LSPs (22% of the 99 1FHL LSP associations), 7 ISPs (13% of the 61 1FHL ISP associations), 6 HSPs (4% of the 162 1FHL sources), and 8 sources with no SED classifications (11% of the 71 1FHL sources with unclassified SEDs). One of the noteworthy characteristics is that most of the 1FHL sources identified as variable belong to the blazar subclass LSP, not to the dominant HSP subclass, which also has a larger number of high-energy photons. It is worth noting that the three classic VHE

absorption, which is energy dependent, or because of a steep decrease with energy of the number of high-energy particles (presumedly electrons/positrons) that are responsible for the high-energy γ rays.

[7]The data used to produced the left panel from Figure 4 is actually the same used in the 2LAC, with the only difference being the selection of the blazar sample: only 194 1FHL blazars (FSRQs+BL Lacs) are being used here.

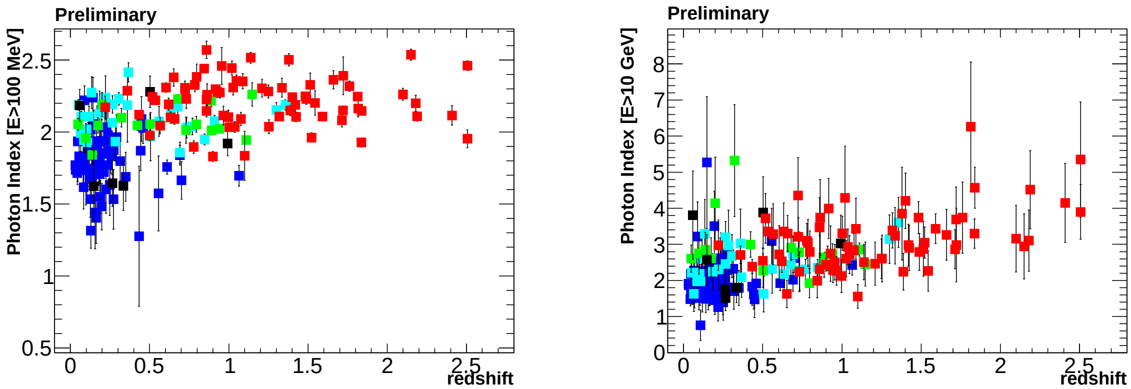

Figure 4: Power-law index versus redshift for the 1FHL sources with available redshifts. The *left* panel shows the power-law index describing the spectral shape above 100 MeV (extracted from the 2FGL catalog) and the *right* panel shows the power-law index describing the spectral shape above 10 GeV (*this work*). In both panels, red indicates FSRQs (71 sources), dark-blue for HSP-BL Lacs (73), light-blue for ISP-BL Lacs (27), green for LSP-BL Lacs (16), and black for BL Lacs with unclassified SEDs (7).

blazars with the highest measured variability above a few hundred GeV, namely Mrk 421, Mrk 501 and PKS 2155−303 (which are HSPs) are not found to be variable in the 1FHL catalog. This is surprising, given that these three also have the largest numbers of detected photons above 10 GeV: 432, 247, and 132, respectively. Moreover, the fraction of 1FHL LSPs identified as variable (∼22%) is substantially higher than the fraction of 1FHL HSPs identified as variable (∼4%). This trend was already observed in the 2FGL blazars at energies above 100 MeV, and reported in the 2LAC paper (e.g., see Figs. 26 and 27 of that work). Therefore, we can confirm that across the entire energy range of the LAT, the LSPs are more variable than the HSPs. These experimental observations show that the variability in the falling segment of the high-energy (inverse Compton) SED bump is greater than that in the rising segment of the SED bump.

2.4. Good Candidates for VHE Detection

As mentioned above, the number of known VHE sources is ∼100, which is a low number in comparison with the ∼1000 γ-ray sources reported by *Fermi*-LAT , and the many thousands reported at radio/optical/X-ray frequencies. This low number of VHE sources precludes detailed population studies, which are crucial to understand the physical properties of the various source types and move toward unification schemes.

The most sensitive instruments to perform VHE astronomy are the Imaging Atmospheric Cherenkov Telescopes (IACTs), which detect γ-rays through the observation of the (extended air) electromagnetic shower induced by the γ-ray in the Earth atmosphere. The main reasons for this very low number of known VHE sources (mostly discovered by IACTs) are (a) the narrow field of view $(3^\circ - 5^\circ)$ of IACT cameras, hence requiring many pointings to scan a region of the sky, (b) the ∼10% operational duty cycle (∼1000 hours annually), because IACTs can only operate on moonless nights with good weather conditions, and (c) the low photon count at VHE, hence requiring long observing times. In order to increase the efficiency of the searches for new sources at VHE with IACTs, one can exploit the all-sky coverage capability, the large duty cycle, and the high γ-ray energy band of *Fermi*-LAT to guide IACT observations toward these sources with high chances of being VHE emitters.

We identified 213 1FHL sources as good candidates for being VHE emitters. and be potentially detected with the current generation of ground-based γ-ray instruments. This list consists of 1FHL sources that have not been detected at VHE but have properties similar to the 84 1FHL sources that have associations with known VHE sources, and is based on the following selection criteria: (a) Index10GeV < 3; (b) Sig30GeV >3; and (c) F50GeV > 10^{-11} ph cm^{-2} s^{-1}. The parameter Index10GeV is the spectral index above 10 GeV, which is directly one of the parameters from the spectral fits, while F50GeV is the estimated flux above 50 GeV, which is a derived quantity from the spectral fits above 10 GeV. The parameter Sig30GeV is the *pseudo significance* of the signal above 30 GeV, which is a derived quantity computed as $\sqrt{TS30\_100GeV + TS100\_500GeV}$, where TS30_100GeV and TS100_500GeV are the test statistic values for the energy bands 30–100 GeV and 100–500 GeV, respectively. Although the three parameters used above are highly correlated, the best indicator of the "VHE-detectability" is F50GeV; the greater the estimated flux above 50 GeV with *Fermi*-LAT, the higher the VHE flux, and hence the easier to be detected with ground-based γ-ray instruments.

A subset of the above-mentioned list of VHE source candidates, namely the ones with F50GeV $> 3 \cdot 10^{-11}$ ph cm^{-2} s^{-1}, was released to all major IACTs in September 2012. One of the interesting characteristics about this list of VHE candidate sources is the presence of 18 high-redshift ($z \gtrsim 0.2$) blazars. High-redshift sources are important for two reasons, *(i)* population studies related to the potential cosmological evolution of the γ-ray emission of blazars, and *(ii)* studies related to the properties of objects, and radiation fields that are located between us and the blazars at cosmological distances. Many of these sources will be observed and detected by all IACTs over the coming years. Every new VHE discovery implies that the known VHE sky increases by $\sim$1%, and the high-redshift sources, if/when detected with IACTs, will expand the volume of the known Universe at VHE, hence enabling the study of their cosmological evolution.

Acknowledgments

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

References

Abdo, A. A., Ackermann, M., Agudo, I., et al. 2010, ApJ, 716, 30
Ackermann, M., Ajello, M., Allafort, A., et al. 2011, ApJ, 743, 171
Ackermann, M., Ajello, M., Albert, A., et al. 2012, ApJS, 203, 4
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, ApJS, 123, 79
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Scargle et al. 1998, ApJ 504, 405
Scargle, J. D., Norris, J. P., Jackson, B., & Chiang, J. 2013, ApJ, 764, 167